HIGH CURRENT RELATIVISTIC ELECTRON BEAM PROPAGATION IN HIGH NEUTRAL PRESSURE ENVIRONMENTS[$]

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Abstract

High current intense relativistic electron beam (IREB) propagation is intrinsically unstable in high pressure environments (HPE) due to the onset of the resistive hose instability. One of the ways to reduce the growth of the hose is through beam conditioning which consists of emittance tailoring and current centroid sweep damping. In the experiments reported in this work we conditioned the SuperIBEX IREB using IFR and active B_θ cells. The conditioning cells succesfully stabilized the beam for approximately 20 betatron wavelengths (λ_β) and propagation lengths exceeding 5 m.

INTRODUCTION

Long range propagation of IREB's in HPE can be accomplished by bursts of beam pulses. The range of each succesive beam is extended because a reduced density channel is generated and is extended with each succesive beam pulse. These multipulse schemes are necessary because of the limited propagation range of the beam due to scattering of the beam electrons from electron-neutral collisions. The characteristic length for the e-folding of the beam radius due to this scattering is the Nordsieck length (L_n). For these schemes to succeed, the first pulse, known as the lead pulse, must propagate stably over its entire range since subsequent pulses are guided by the density channel generated by it.

Beam conditioning extends the range of "stable" propagation of the lead pulse since it suppresses the growth of dominant instability, namely the resistive hose. The resistive hose is a result of the interaction of the electron beam with the return currents generated in the plasma formed by impact ionization of the gas along the beam path and driven by the beam. The return currents exhibit a resistive phase lag, a necessary ingredient for the generation of the hose. Beam conditioning consists of emittance tailoring and current centroid oscillation (beam sweep) damping. Emittance tailoring reduces the resistive hose growth by continuously changing the betatron wavelength (λ_β) within the pulse, thus detuning and phase mix damping the instability. Stable propagation requires that the equilibrium radius profile of the propagating beam is monotonically decreasing in time through a large portion of the beam current pulse. Stability usually improves if the conditioning extends well into the body of the beam.

Beam sweep reduction is equally important in suppressing the resistive hose since it provides the initial perturbation that gives rise to the instability. One important side effect of sweep reduction is that the beam emittance increases during the damping process, subsequently causing beam radius growth. Emittance grows because all oscillation damping schemes convert beam radius and centroid oscillation into emittance.

Resistive hose oscillations are separated into low (<100 MHz) and high (>100 MHz) frequency hose. Both modes are equally dangerous but they behave differently. Recent experiments performed on the RADLAC accelerator [Sandia Reference] indicate that the non-linear phase of the high frequency resistive hose may exhibit amplitude saturation. Low frequency hose observations are more difficult because they not only require a very stable beam to allow observable growth. It is difficult to distinguish low frequency hose from aiming inaccuracies because the measurement of the beam centroid position is imprecise.

Lead pulse stability can be parametrized by two dimensionless parameters. The ratio of Nordsieck length to betatron wavelength (L_n/λ_β) must be relatively high to avoid hose stabilization through beam heating. This number represents the number of instability growth times available before the heating effects suppress the instability. As the beam heats the local betatron wavelength increases resulting in slower instability growth. The second number is the ratio of the distance of stable propagation to the betatron wavelength (R/λ_β). This represents the number of instability growth times before any beam disruption occurs.

IFR cells can tailor the radius of IREB's for long propagation experiments [1,2]. Even though IFR cells can center the beam and damp the sweep [3] they have no effect at all on the beam head which plays a critical role in the stabilization. The sweep damping and centering is weak especially for large wall radius, low pressure IFR cells like the one used here. More efficient sweep damping and beam centering can be accomplished using an active B_θ cell. Beam centering is not required for stability as long as there is no sweep, but allows aiming of the beam thus facilitating measurements of low frequency hose motion. The B_θ cell employs a thin current carrying wire along the beam axis [Murphy et al., these proceedings]. The wire current flows in the same direction as the beam current. Sweep damping is achieved because the force exerted by the current carrying wire on the beam is anharmonic. The cell centers the beam because it converts any radial excursion of the beam into emittance.

Beam radius tailoring can be quantified using three parameters [1]. A parameter n which represents the ratio of the radius of the freely expanding beam head to the pinch point radius of the beam. This is not always the tail radius because some conditioning schemes overheat the beam tail resulting in radius flaring. R_{eq} is the asymptotic value that the beam radius approaches in the absence of tail overheating and t_c is the time constant for the radius to reach equilibrium.

Electron beams can be tailored by a variety of techniques ranging from single or double IFR cells, active and passive vacuum or high pressure wire cells, transverse conducting foil arrays and hybrid cells. In addition to radius tailoring, the transport efficiency, beam centering , sweep reduction and damping properties of the cell must be considered in the conditioning cell selection for lead pulse propagation experiments. This work concentrates primarily on a beam radius tailored by a single low pressure IFR cell or a hybrid cell with the IFR cell followed by an air filled active B_θ cell.

EXPERIMENT DESCRIPTION

The lead pulse stability experiments were performed with the beam produced by NRL's SuperIBEX accelerator. The nominal beam energy is 4.5 MeV and the pulse width is 40 nsec FWHM. The beam is extracted from the cold cathode diode through an emittance selector consisting of a 5 cm long, 18 mm diameter evacuated stainless steel tube and an exit foil which allows control of the current and input beam emittance. The beam is immediately injected into an IFR cell for radius tailoring. The typical beam

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current injected into the IFR cell ranges from 15-27 kA. The IFR cell is 40 cm long, 10 cm in diameter is filled with argon and has interchangeable input and output foils. The standard IFR input foil is 38 μm thick titanium foil. The exit foil was 38-500 μm titanium. The foil provides the input beam with enough emittance to extent the tailoring duration at least up to the peak of the current pulse without significant current losses associated with beam head erosion and wall contact for a hot beam. The first sequence of stability experiments was performed with just the IFR cell. The exit foils used for these experiments ranged in thickness from 3–20 mils of titanium. The beam currents for the IFR only shots were 10–21 kA.

To further stabilize the beam, the IFR cell was followed by a 120 cm long active wire B_θ cell. The cell was fed by a capacitor bank with currents as high as 12 kA. Because of the long risetime of the capacitor bank, the wire current was practically constant throughout the beam pulse. A schematic of the most complicated setup consisting of the IFR and B_θ cells as well as an optical diagnostics cell is shown in figure 1.

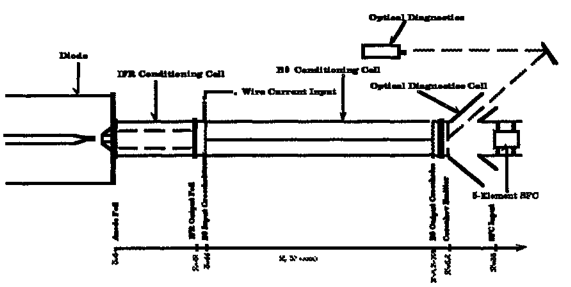

Figure 1 Schematic diagram of the IFR/B_θ conditioning cell used in the lead pulse stability experiments. The optical diagnostics cell with the Cerenkov target and the segmented Faraday collector is also shown.

The conditioned beam was injected into a 2 m diameter chamber. The chamber length was 5 m. To extend the range two 50 cm segments of 50 cm diameter pipe was placed before the large propagation chamber.

The main diagnostics used to measure the propagation parameters were:

- Beam bugs for beam current and centroid position measurements near the entrance and exit of the IFR cell.
- 5 element concentric segmented Faraday (SFC) collector for beam current distribution measurements between 5 cm and 66 cm away from the exit foil [4].
- 4 frame gated optical imager with 100 picosecond resolution measuring time resolved 2-dimensional beam current distribution from Cerenkov emission of a thin FEP Teflon foil .
- Optical streak camera for time resolved 1-D measurements of beam current distribution, radius and centroid position from Cerenkov emission of a thin FEP Teflon foil. The Cerenkov foil for the optical diagnostics was placed at several distances from the exit of the conditioning cell to measure the equilibrium beam properties even in the case of mismatched injection in the air.
- Azimuthal magnetic probe sets for net current and centroid position throughout the beam propagation range
- Time integrated side-on photographs of the beam induced atmospheric emissions yielding information about beam radius growth in air.

Results and Discussion

There are several parameters that affect the stability properties of an IREB propagating in the atmosphere without wall assistance. The beam emittance which severely affects the equilibrium radius, the radius tailoring time and its temporal relation to the beam current rise, the beam current and the beam sweep.

To examine the effect of beam emittance variation we selected to propagate the beam exiting an IFR cell. The exit beam emittance profile was changed by varying the IFR cell exit foil thickness which affects the equilibrium radius and peak current density. A 38 μm thick titanium foil was used at the input of the IFR to provide a long tailoring ramp that extended to the peak of the current and reduce tail overheating. The parameters of the beam reaching the IFR exit foil were:

- Equilibrium half-current radius ≈ 1.0 cm
- Peak beam current ≈ 14 kA
- Beam sweep ≈ ± 3 mm
- Tailoring ratio ≥ 4

For exit foil thickness below 250 μm the beam became progressively more unstable with decreasing foil thickness. Stable beams required thick exit foils compared to the input foils, which dominate the beam emittance and directly convert radius tailoring in the IFR cell to emittance tailoring. Figure 2.a is a time integrated photograph of the beam air fluorescence for a beam exiting through a 125 μm titanium foil and figure 2.b is for a 250 μm titanium foil. The colder beam shows large growth of the non-linear hose within the first 2 meters of propagation.

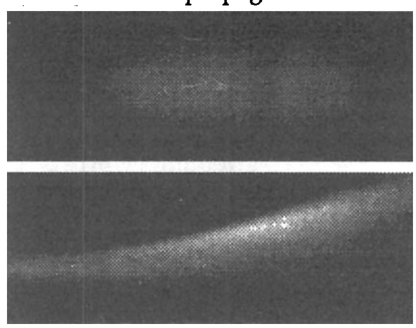

Figure 2 a–Side-on time integrated photograph of the beam induced air fluorescence for a 14 kA beam exiting the IFR cell through a 125 μm thick titanium foil. b–The same beam exiting through a 250 μm thick foil.

To examine the effect of tailoring length on stability we also chose to use a beam conditioned by a single IFR cell. The tailoring length can be changed by simply changing the IFR fill pressure [1]. IFR pressures of 3, 5 and 9 mTorr of argon were selected. The thinnest exit foil required for stability was 250 μm compared to the 38 μm IFR input foil, thus the radius tailoring was again directly converted to emittance tailoring. The beam equilibrium radius at the exit foil was approximately 1 cm for all cases. The tailoring lengths ranged from 6 ns at 9 mTorr to 25 ns at 3 mTorr. Figure 3.a shows the tighter beam that results from the 9 mTorr fill but also the instability growth also with the first two meters of propagation. The stable 5 mTorr case is shown in figure 2.b.

Figure 3.b shows the open shutter photograph of the air fluorescence when the beam current increases from 14 to 24 kA. The IFR tailoring measurements indicate that for the parameters of our experiments the beam current has no significant effect on the radius tailoring profile. It is possible that the rapid loss of stability is due to the increased current density of the higher current beam since the beam radius was unchanged. Higher sweep amplitude could also destabilize the beam, but the measurements do not indicate significant sweep growth inside the IFR cell.

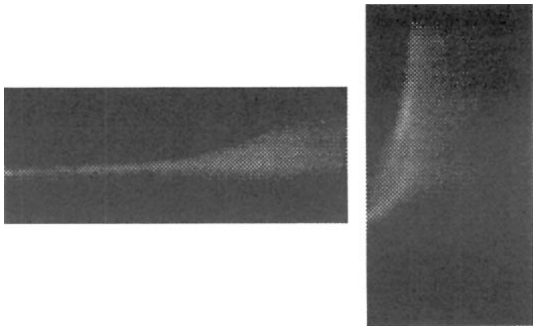

Figure 3 a–Side-on time integrated photograph of the beam induced air fluorescence for a beam exiting the IFR cell with 9 mTorr Argon fill. b–The same photgraph for a 24 kA beam

In order to stabilize even the optimally tailored IFR beams we needed rather thick foils for our beam and the added temperature resulted in large beams (≈ 2–3 cm radius) with radius e-folding lengths of approximately 2.5 m as measured by the side-on photographs. The air glow photograph is fitted by a gaussian profile at each z position from which the beam radius and center are obtained. An exponential is then fitted to the data with the e-folding length and injection radius as its parameters. The time integrated photographs provide information primarily about the beam body. The dynamic range of photographic film is very limited and so the emission of the high current, tight beam body dominates over the diffuse, low current beam head. These measurements however tend to overestimate the radius since emission due to the return currents in the beam generated plasma as well as any beam sweep result in broadening of the image on the film.

When the 1.2m long, 20 cm diameter high pressure B_θ cell was added following the IFR cell with a 38 μm exit foil the output beam was stabilized. B_θ cells result in moderate increase of beam temperature even for relatively high wire current operation (≈ 50% of the beam current) which seems to optimize their transport efficiency and conditioning properties. The stable output beam was colder that the IFR cell with the 250 μm thick exit foil effectively increasing the beam radius e-folding length. The peak transport efficiency for the B_θ cell was approximately 65% and occured with a

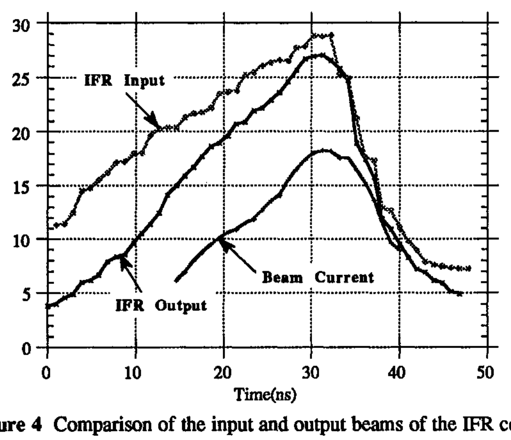

Figure 4 Comparison of the input and output beams of the IFR cell and the output beam from the B_θ cell.

wire current of 10 kA and an injected beam current of 25-27 kA.

The beams injected into the air had currents in the 15–18 kA range. Figure 4 shows the input and output currents of the IFR cell as well as the total beam current exiting the B_θ cell. Figure 5 shows the beam radius and peak on-axis current density profiles 30 cm downstream from the exit of the conditioning cell measured by the SFC. The beam radius was 1.6 cm and the current density was ≥1.8 kA/cm^2.

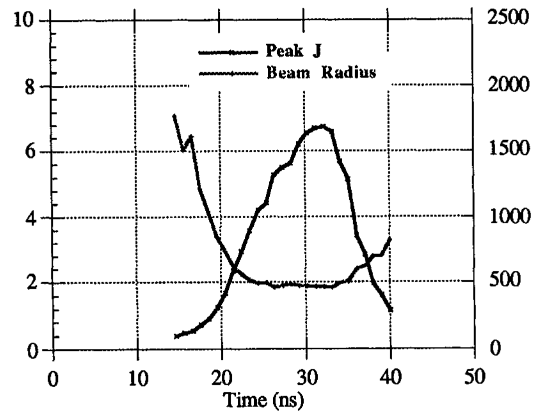

Figure 5 Beam Gaussian radius and peak current density profile for the typical beam used in the stability studies.

B_θ cells seem to convert input radius tailoring directly to emittance tailoring. The equilibrium radial profiles for 3, 5 and 9 mTorr IFR/B_θ cell hybrid with a 38 μm foil interface are shown in figure 6. The corresponding IFR only results with a 125 μm thick exit foil are shown in figure 3 of reference 1. The experiments show that IFR cells with thick exit foils result in virtually identical emittance tailoring as the IFR/B_θ hybrid cell with a much thinner interface foils. For our conditions the B_θ cell heats the beam like an 87 μm thick titanium foil.

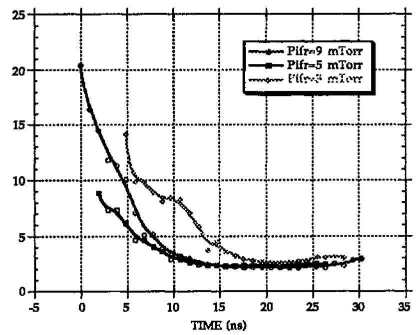

Figure 6 IFR/B_θ equilibrium radius profiles for varying IFR pressure with a 38 μm thick Ti interface foil. The B_θ cell maintains the radius tailoring which is virtually identical to a single IFR cell with 125 μm thick Ti foil.

When the tailored beam from the hybrid cell is injected into the 2 m diameter tank, the net current and its centroid location are measured at several downstream locations ranging from 0.2–5 m from the end of the conditioning cell. A typical set of net current and x and y displacement traces obtained on a single shot are shown in figure 7. The experiments are performed in the high return current regime since the net current measured by the downstream probes on a 50 cm radius circle centered on the tank axis is 9.5-11 kA. The return currents therefore are as high as 50% of the beam current which ranges from 16–18 kA. For the measured net current the computed L_n/λ_β for this beam is approximately 20.

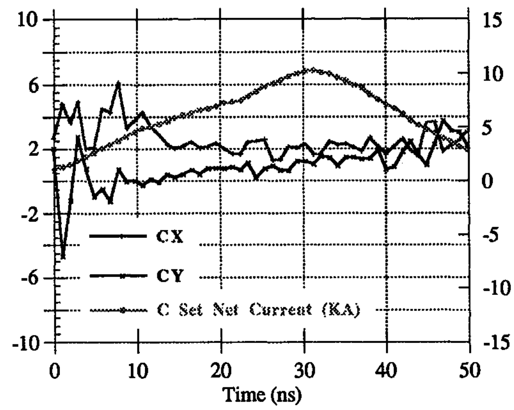

Figure 7 Net current and centroid position for a stable beam conditioned with IFR/B_θ hybrid cell 2.5 m downstream of the conditioning cell. The injected beam current is 18 kA peak and the radius at injection is 1.3 cm.

A compilation of the results of a series of stable shots is shown in the report by Murphy et al. [5].Three sets of probes are located 1.3, 2.5 and 4.5 meters downstream of the cell exit. Each point on the graph is the average location of the net current centroid for an entire pulse and the error bars represent the mean deviation in the x and y directions. The beam is quite stable because even at 4.5 m the mean centroid deviation from center is about 5 cm which is only a small fraction of the expanded beam radius at this location. The centroids at the 3 locations are not collinear for each shot, indicating that low frequency hose motion and not beam aiming error could be responsible for these deviations.

CONCLUSIONS

Proper beam conditioning and sweep damping using IFR or hybrid IFR/B_θ cell, we have achieved stable propagation of high current relativistic electron beams in full density air. The Nordsieck length/betatron wavelength ratio for the most stable beams is approximately 20. The propagation range exceeds 5 m without indications of a serious instability. Beams without the B_θ cell are harder to stabilize and had to be heated to a larger radius and lower current density to achieve stability.

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